Binaries Like to be Twins: Implications for Doubly Degenerate Binaries, the Supernova Ia Rate and Other Interacting Binaries

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ABSTRACT

The recent sample of 21 detached eclipsing binaries in the Small Magellanic Cloud (Harries et al. 2003, Hilditch et al. 2005) provides a valuable test of the binary mass function for massive stars. We show that 50% of detached binaries have companions with very similar masses, $q = M_2/M_1 > 0.87$, where M_1, M_2 denote the masses of the two binary components, $M_1 \geq M_2$. A Salpeter relative mass function for the secondary is very strongly excluded, and the data is consistent with a flat mass function containing 55% of the systems and a "twin population with $q > 0.95$ containing the remainder. We also survey the vast existing literature discussing the mass ratio in binaries and conclude that a significant twin population (of more than 20-25%) exists in binaries that are likely to interact across a broad range of stellar masses and metallicity. Interactions involving nearly equal mass stars have distinctly different properties than those involving stars of unequal mass; the secondaries will tend to be evolved and the common envelope evolution is qualitatively different. The implications of such a population for both binary interactions and star formation are substantial, and we present some examples. We argue that twin systems may provide a natural stellar population to explain the recently proposed prompt channel for type Ia SN, and the presence of a twin population dramatically reduces the maximum inferred NS+BH merger rate relative to the NS+NS merger rate. Twins may also be important for understanding the tendency of WD and NS binaries to be nearly equal in mass, and inclusion of twins in population studies will boost the blue straggler production rate.

Subject headings: binaries: eclipsing – stars: early-type – stars: formation – supernovae: general

1. Introduction

A majority of stars are in binaries, and a substantial fraction of binaries have short enough orbital periods that they are likely to interact during either their main sequence or post-main sequence evolution. Many of the most interesting phenomena in astronomy can be directly traced to the interaction of close binaries; an incomplete list would include binary neutron stars and white dwarfs, SNIa, cataclysmic variables, and blue stragglers. There is a substantial literature on the subject (e.g. Paczynski 1971). Although there are many ingredients that must be considered in interacting binaries, an implicit assumption in much theoretical work has been that the lifetimes of the stars are almost always quite different. This arises naturally from two considerations. First, the strong mass-lifetime relationship for all but the most massive stars implies a large lifetime difference unless the masses are very close. Second, the single star IMF is a steep function of mass, with low mass stars being far more numerous than high mass stars (e.g. Salpeter 1955). If a similar relative mass function applies to binaries, equal mass systems are exceedingly unlikely. Most population synthesis studies adopt a flat mass spectrum for systems that are likely to interact, following longstanding evidence that a steeply rising relative IMF is unlikely (see for example Kuiper 1935). However, even a flat relative IMF still yields relatively few systems with very similar masses. Motivated by recent papers on the production rate of double compact systems and the possible existence of a prompt channel for type Ia supernovae (both discussed in Section 4), we investigate the properties of massive close binaries.

In this paper we present evidence in a sample of massive eclipsing SMC stars for a substantial population of nearly equal mass binaries. In such systems a strong inequality in lifetime is not present, and there will be important qualitative differences in their evolution compared to unequal mass binaries. Furthermore, we argue that recent data in the literature is entirely consistent with "twins" being a general feature of close binary population. Our evidence for the presence of a significant population of twins is presented in Section 2. We discuss other evidence from the literature in Section 3. We consider the implications for interacting binary evolution in Section 4.

2. Sample and Analysis of Massive Binaries in the SMC

Harries, Hilditch & Howart (2003; hereafter HHH03) and Hilditch, Howarth & Harries (2005; hereafter HHH05) obtained accurate spectroscopic data to derive a complete set of physical parameters for 50 eclipsing binaries found by the Optical Gravitational Lensing Experiment in the Small Magellanic Cloud (Udalski et al. 1998; Wyrzykowski et al. 2004). As discussed by HHH05, their "full sample of 50 OB-type eclipsing systems is the largest

single set of fundamental parameters determined for high-mass binaries in any galaxy". Of these 50 systems, they find 21 are in detached configurations, 28 are in semi-detached configurations indicating mass transfer has occurred, and one is a contact binary. Multi-epoch spectroscopic data were obtained for a larger sample of 169 systems (all of them with orbital periods $P < 5$ days), but reliable orbital solutions were derived for the subset of 50 systems. The masses derived for the individual stars in the binaries are typically uncertain at $\pm 10\%$, with mass of the primary (more massive) star ranging from $6.9\ M_{\odot} < M_1 < 27.3\ M_{\odot}$.

The mass ratio q defined as $q = M_2/M_1$, where $M_1 \geq M_2$, can be simply derived from the semi-amplitudes K_1, K_2 of the radial velocity (RV) curves $q = K_1/K_2$, and we show these values for their full sample of 50 stars in Fig.1. With filled circles and errorbars we show the sample of 21 detached (before any mass transfer occurred) systems, while with open circles we show 28 semi-detached and one contact binary. The median mass ratio is $q = 0.87$ for the detached sample and $q = 0.65$ for the semi-detached/contact sample—a striking difference. While it is not surprising that the median q value for the semi-detached systems, which underwent mass transfer, is far from unity, it is very surprising that 13 out of 21 detached systems have $q > 0.85$. At least at face value, it seems that given the mass of the primary in a binary, for detached and therefore unevolved systems in about 50% of cases the mass of secondary is within 15% of the mass of the primary, i.e. they form what we will call (following Tokovinin 2000 and Halbwachs et al. 2003, see next Section) "twins".

Could that be the result of an observational bias? Clearly, it is easier to detect eclipsing binaries when the two stars are of similar size and brightness. It is also easier to measure the radial velocities of the two components if they are of similar brightness and mass. However, while some biases are certain to be present, it is very unlikely that the twin population in the SMC sample is a result of selection effects. There are detached systems present in the sample with q values as small as 0.55. In addition, the semi-detached sample has been selected from the same photometric sample, observed spectroscopically in an identical fashion, and thus forms an ideal control sample. The fact that it has a dramatically different distribution of q from the detached sample (the K-S probability that they are drawn from the same distribution is 0.002), while expected from binary evolution, reinforces that reality of the unexpected q distribution for the detached sample.

Given the above, we can now test statistically the various proposed distributions of q value in this interesting mass range. For this purpose we considered two different models for the distribution of q: a flat mass distribution $p(q) = const$ and a Salpeter (1955) relative mass function, $p(q) \propto q^{-2.35}$. We assumed that observational selection effects would cut off the q distribution below 0.5, so both the flat and Salpeter mass functions were truncated at that value. These distributions are illustrated in Fig. 2. Both the Salpeter and flat

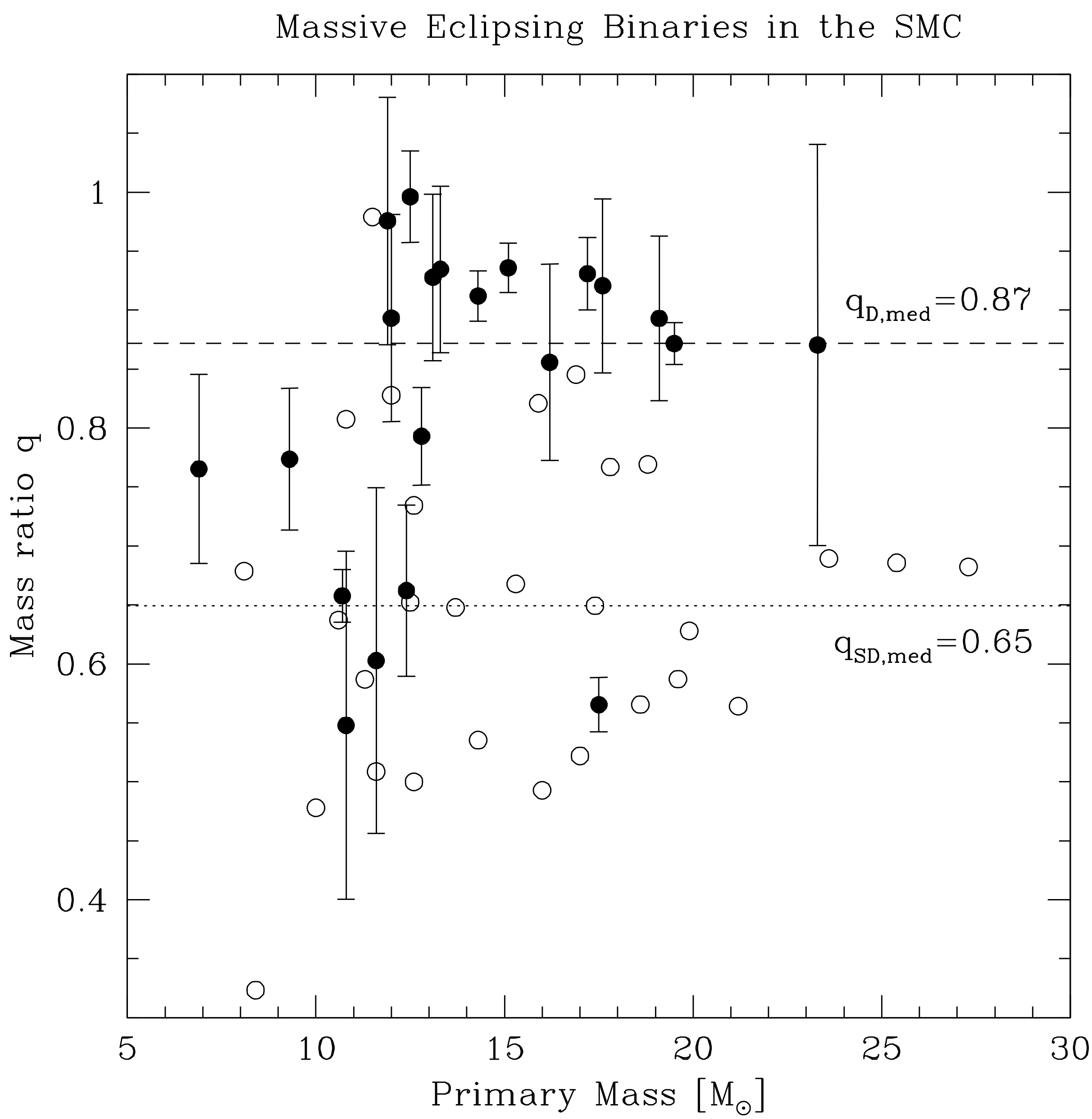

Fig. 1.— Mass ratio $q = M_2/M_1$ for a sample of 50 OB-type eclipsing binaries from the SMC (Harries et al. 2003; Hilditch et al. 2005) shown as a function of the primary mass M_1. With filled circles and errorbars we show the sample of 21 detached (unevolved) systems, while with open circles we show 28 semi-detached and one contact binary. The median mass ratio is $q_{D,med} = 0.87$ for the detached sample and $q_{SD,med} = 0.65$ for the semi-detached/contact sample.

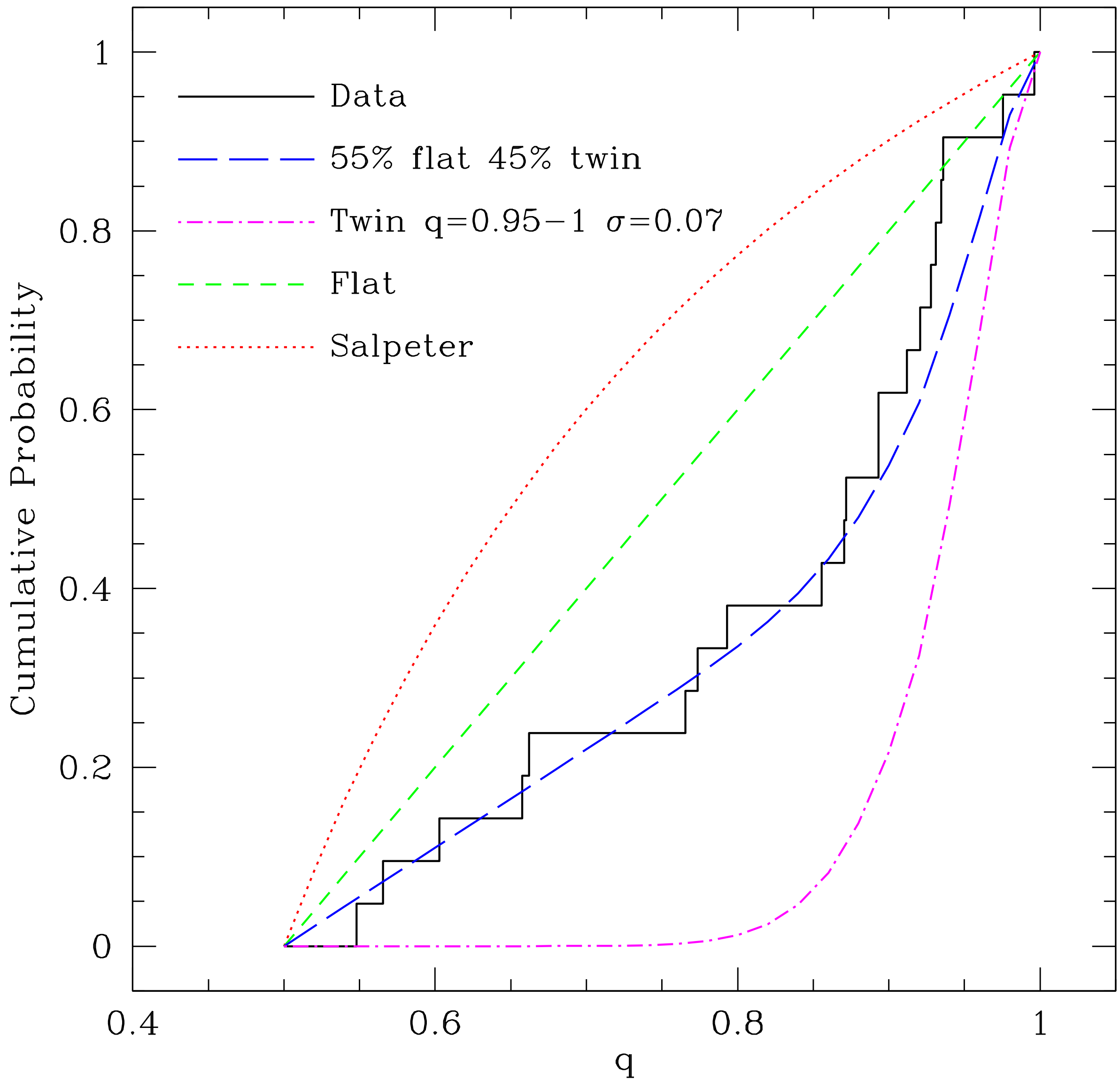

Fig. 2.— The cumulative probability distribution of 21 SMC detached eclipsing binaries as a function of the mass ratio $q = M_2/M_1$ are compared with different model distributions. The data (thick solid line) are taken from Harries et al. (2003) and Hilditch et al. (2005). The Salpeter relative IMF (dotted line) is clearly incompatible, and a flat distribution (short-dashed line) is also unlikely. A fit including twins (45% twins, 55% flat) is given as the long-dashed line, and the twin component alone ($q = 0.95$ to 1 convolved with an observational error of 0.07) is indicated by the dot-dashed line.

mass functions are inconsistent with the observed data (probabilities of 3.4×10^{-3} and 0.02, respectively). By varying the twin fraction we found that the best fit was obtained with a flat component of 0.55 +/- 0.15 combined with a twin distribution from q = 0.95 to 1 convolved with the observational error $\sigma(q) = 0.07$; this is shown for comparison in Fig. 2. Based on this, we conclude that there is clear evidence for two populations of eclipsing binaries, and that a substantial fraction of them must be of nearly equal mass. Even if we assume that the absence of systems with mass ratios lower than $q = 0.5$ is a selection effect, we still require a significant twin population of 20-25% with $q > 0.95$ in the short period binary population (in addition to the 5% of such stars that would naturally be present in a flat relative IMF).

3. Other Evidence for a Significant Twin Population

Because of the striking consequences of this result, it is reasonable to ask how general it might be. Fortunately, there has been an dramatic increase in the quantity and quality of data in the last few years. Recent radial velocity surveys have provided large samples of spectroscopic binaries. Microlensing and planet eclipse studies have provided a wealthy of information on eclipsing binaries. In addition, IR speckle studies in nearby open clusters have provided valuable information on longer period systems. The picture that emerges is consistent with the idea that there are three natural components of the relative binary mass function. At long orbital periods ($P > 10$ yrs) there is no evidence for a peak at q = 1 and the binary masses appear to be uncorrelated. However, for short period systems a Salpeter relative IMF is ruled out in a number of different domains: for example, field F and G stars (e.g. Halbwachs et al. 2003; Lucy & Ricco 1979); field halo stars (e.g. Goldberg, Mazeh & Latham 2003); massive stars (e.g. Garmany, Conti & Massey 1980; this paper).

In addition to clear evidence for a flat component, a peak near $q = 1$ was reported by several investigators. For example, Halbwachs et al. (2003) studied a large sample of spectroscopic binaries type F7 to K (masses from about 1.7 down to 0.5 $M_{\odot}$), including binaries in open clusters (Pleiades and Praesepe). They find that the mass ratio has a broad peak from $q \approx 0.2$ to $q \approx 0.7$, and a sharp peak for $q > 0.8$ (what they call "twins"). As they discuss, the strength of the peak for $q > 0.8$ gradually decreases with the increasing orbital period, which is to be expected. In addition, independent of period, the twin population has significantly lower eccentricities compared to the other binaries, strongly suggesting a different formation mechanism. The fraction of twins (see their Fig.9) can be as high as 50% for periods $P < 10$ days and it is still significant (as high as 35%) for much longer periods of up to 1000 days.

A much earlier study by Lucy & Ricco (1979) also finds a strong and narrow peak of

binaries with $q \approx 0.97$, again using a sample of spectroscopic binaries corrected for various observational errors and biases. Tokovinin (2000) confirms that finding using additional modern data and in fact also calls this population "twins", arguing that they constitute 10-20% of the total binary population in the $P = 2 - 30$ days regime.

All these results most strongly suggest that the striking trend found in this work for massive eclipsing SMC binaries is a general feature rather than either a peculiar environmental effect or an observational selection effect. In fact, it can be said that twins have been present in most of such studies, even if not always recognized as such.

Additional, although perhaps more anecdotal support for the significant twin population comes from the realms of very high, and also very low mass stars found in eclipsing binaries. The most massive binary known, WR 20a (Rauw et al. 2004; Bonanos et al. 2004), contains $82.7 \pm 5.5\ M_\odot$ and $81.9 \pm 5.5\ M_\odot$ components (Rauw et al. 2005). The system happens to be an eclipsing binary (Bonanos et al. 2004), so the masses of both components can be measured accurately. The mass ratio for this system is $q = 0.99 \pm 0.05$, and it would be most interesting to measure this ratio to even higher accuracy, to see if this system is indeed an "identical twin". Given that 80 $M_\odot$ stars are extremely rare (both due to the steepness of the mass function and their short lifetime), having such a massive secondary would be most unlikely unless the twin phenomenon is involved.

For very low stellar masses, several detached eclipsing binaries have equally or even more strikingly close to $q = 1$ values. Lopez-Morales & Ribas (2005) report a new low-mass, double-lined, detached eclipsing binary, GU Boo, with $M_1 = 0.610 \pm 0.007\ M_\odot$, $M_2 = 0.599 \pm 0.006\ M_\odot$, i.e. $q = 0.98 \pm 0.02$. This is a very similar system to the well-studied low mass eclipsing binary YY Gem, which as shown by Torres and Ribas (2002) has two components "which are virtually identical to each other", with a mass of $M_{1,2} = 0.5992 \pm 0.0047\ M_\odot$ and $q = 1.0056 \pm 0.0050$, a truly "identical twin". Even lower mass detached eclipsing system, CM Dra, has a mass ratio of $q = 0.9260 \pm 0.0026$, and $M_1 = 0.231\ M_\odot$ (Metcalfe et al. 1996), again very close to $q = 1$. It should be said that there are very few such law-mass detached eclipsing binaries known, making the very close values of "q" described above even more striking.

While we most strongly argue for the existence of a significant, at least 20% and maybe as high as 50% twin population, based on the work in this paper and a vast body of work described in the literature, additional studies of the twin population would be most useful. For example, as mentioned earlier in this paper, the sample of 50 SMC binaries studied by HHH03 and HH05 comes from a much larger sample of 169 eclipsing binaries they observed spectroscopically. Even if the RV solutions for the remained of the sample are not good enough to study their detailed properties such as mass, it could possibly be used to study

the distribution of q, especially if additional RV epochs could be obtained. There is also a large OGLE catalog of 2580 eclipsing binaries in the LMC (Wyrzykowski et al. 2003), which could be used to select bright targets for analogous RV study in that galaxy.

4. Discussion

4.1. Implications for the Binary Neutron Star Birthrate

The first application of our result is to the inferred production rate of binary neutron stars (NS+NS) and neutron star + black hole (NS+BH) systems. The production of double compact systems is a result of close binary interactions. The primary will experience a supernova first if $M_p > M_{crit}(NS)$. It will leave a black hole if $M_p > M_{crit}(BH)$ and a neutron star otherwise. However, Bethe, Brown, and Lee (2005a,b; hereafter BBL05) argue that mass transfer from the envelope of the secondary onto the compact object will lead to strong accretion, resulting in a black hole remnant from the primary unless the secondary is very similar in lifetime and mass to the primary. Furthermore, they adopt a steep mass function for the mass of the secondary relative to the primary (Salpeter 1955), which makes such a near equality in mass unlikely. They therefore argue that there should be a large population of NS+BH systems relative to the NS+NS population. Any given measurement of the NS+NS population therefore would imply the presence of a much larger NS+BH population. Although the latter population would be difficult to detect directly, it would produce a large signal in gravitational wave experiments such as LIGO.

BBL05 adopted $M_{crit}(NS) = 10\ M_\odot$ and $M_{crit}(BH) = 20\ M_\odot$, requiring masses equal to within 4% to produce NS+NS systems and otherwise producing NS+BH systems. They also assumed both the primary and secondary mass functions were slightly steeper than the Salpeter IMF, namely $dn/dm \propto m^{-2.5}$, and furthermore that the secondary IMF was truncated at 10 $M_\odot$. From this set of assumptions they estimate a NS+BH coalescence rate ten times higher than the NS+NS rate and a detectability of the former twice as high, resulting in a factor of 20 boost in the predicted LIGO rate.

A very different picture emerges from a binary population including stellar twins. In order to estimate the impact of the relative IMF on the double compact object production rate, we proceed as follows. We assume, as per BBL05, that all systems with both primary and secondary masses between 10 and 20 $M_\odot$ will produce double compact object systems; furthermore, we assume that systems where the mass difference is greater than 5% may produce NS+BH systems. We also adopt a Salpeter primary IMF, $dn/dm \propto m^{-2.35}$. We consider three mass function cases: a flat mass function ($dn/dm = const$); a population with

25% twins and 75% drawn from a flat mass function; and a Salpeter relative secondary IMF.

For a flat mass function 24% of the close binaries with primaries in the relevant mass range could produce double compact systems, and 5% of them have masses within 5%. In this case the maximum ratio of (NS+BH)/(NS+NS) systems is 5. The same calculations for a relative Salpeter IMF with a minimum mass of $0.3M_{sun}$ yields 0.32% and 0.044% respectively, for a ratio of 6 (but a very small parent population). However, the twin population would imply that 43% of close binaries could produce double compact systems and 30% would be nearly equal in mass, for an inverted ratio of (NS+BH)/(NS+NS) of 0.3. We therefore conclude that there is no requirement for a large unseen population of NS+BH systems, even before efficiency arguments are accounted for, and that it is therefore unlikely that the LIGO event rate should be substantially amplified by such systems. Population synthesis models (e.g. Belczynski, Bulik & Ruiter 2005) predict (NS+BH)/(NS+NS) rates of less than 1/3 even before twins are accounted for, so that the actual ratio may well be much less than the simple estimates above.

4.2. Implications for the SNIa Rate

The presence of binary twins could have intriguing consequences for the time delay prior to the onset of Type Ia supernovae. The Type Ia SN rate has been measured out to z=1.6 by the GOODs consortium, and the peak in the observed rate occurs at a significantly lower redshift than the peak in the star formation rate. This led Strolger et al. (2004) to infer a long delay time, of order 2-5 Gyr depending upon the assumed functional form for the delay time; a similar timescale of 1.7 Gyr was obtained by Gal-Yam & Maoz (2004). However, studies of the type Ia SN rate in the local universe indicate a strong correlation between the star formation rate and the Type Ia SN rate (Mannucci et al. 2005a). Scannapieco & Bildsten (2005) and Mannucci, Della Valle, & Panagia (2005b) argue that this data requires a two-component model for the SNIa rate: a prompt component with a short delay time (~ 0.1 Gyr) and a delayed component with a timescale comparable to that observed at high redshift (> 1.7 Gyr). The existence of a prompt SNIa component is not inconsistent with Galactic chemical evolution data because it would be correlated with the SNII rate (see Scannapieco & Bildsten 2005). In such models the decrease in [O/Fe] with increased [Fe/H] is caused by the increase in the SNIa rate from the onset of the delayed component rather than from the absence of SNIa at early times.

There are two general formation scenarios for type Ia SN. A white dwarf could accumulate mass from a non-degenerate companion star (e.g. Whelan & Iben 1973), or two white dwarfs could merge (e.g. Webbink 1984). Following Belczynski et al. (2005) the delay

timescale has two main components. Both the primary and secondary must leave the main sequence; this timescale is governed by the lifetime of the lower mass secondary. In the case of binary WD mergers the timescale for coalescence is also important, and it is primarily a function of the orbital separation after the envelopes are removed. The degree of orbital shrinkage in turn depends on the detailed physics of the common envelope phase. We argue that the presence of a substantial fraction of binary twins will have a substantial impact on both of these timescales. The secondary in twin systems will have a lifetime similar to the primary; as a result, the evolutionary delay time will be minimized. A division into two relative mass functions (twin and flat) will naturally lead to a comparable division into evolutionary timescales. However, as we will see below, there are also distinctive features of twin common envelope evolution that could play an addition role.

4.3. Double WD Systems and Common Envelope Evolution

Double white dwarf systems are thought to arise from systems which have experienced two common envelope events, and the white dwarf masses are primarily determined by the orbital separation at the onset of the common envelope phase. Recent observational studies have found that such systems tend to have very similar masses (Maxted, Marsh & Moran 2002). The most natural implication is that the orbital period of the progenitor system must not have changed much during the first common envelope event (to permit similar white dwarf masses), but that it also must have changed dramatically during the second event (to permit the short final orbital periods. Such a configuration is expected to be rare in traditional population synthesis calculations (e.g. Iben, Tutukov & Yungelson 1997). However, Nelemans et al. (2000) and Nelemans & Tout (2005) argue that in their model of common envelope evolution stars of nearly equal initial mass will experience relatively little orbital shrinkage in the first mass transfer event. Although their treatment of the CE phase can reconstruct the observed distribution of short period white dwarf binaries, the absolute rates predicted with a flat IMF are on the low end. The inclusion of binary twins in the relative IMF would solve this potential problem by boosting the production rate. By extension, the inclusion of binary twins could also make it easier to produce pairs of more massive white dwarfs for doubly degenerate SN Ia scenarios.

4.4. Blue Stragglers

Finally, we briefly note the consequences for the production of blue stragglers through binary mergers. Although blue stragglers can be produced by a variety of mechanisms,

one mechanism that is likely to be important is coalescence of a close main sequence binary through angular momentum loss. Both the merger rate and whether a merger is observable as a blue straggler are sensitive to the assumed relative binary IMF (Andronov, Pinsonneault & Terndrup 2005). The inclusion of twins would boost the merger rate because, for old systems, more massive secondaries lose more angular momentum. It would also make the merger products more massive on average and more likely to be detected as blue stragglers observationally.

5. Possible Relevance for Other Studies

Given the origin of this paper (see Acknowledgments), instead of the usual "Summary" we have decided to provide a (naturally, incomplete) list of recent astro-ph postings for which the "binaries like to be twins" result is more or less relevant. In no particular order:

1. The equal masses of the neutron stars observed in the binary NS-NS systems would follow naturally from their evolution from the binary twins system, and probably does not require special tuning, unlike suggested in BBL05 papers. This could be relevant to Piran & Shaviv (2005).

2. In light of recent localizations of short gamma-ray bursts, NS-NS and NS-BH binaries were discussed in a whole slew of recent astro-ph postings (e.g. Villasenot et al. 2005; Fox et al. 2005; Hjorth et al. 2005). As discussed, having a large population of equal-mass binaries directly affects the predicted rates of such events.

3. Another recent GRB event which resulted in a slew of astro-ph postings was the discovery of the $z = 6.3$ GRB 050904 (e.g. Haisplip et al. 2005; Price et al. 2005; Tagliaferri et al. 2005). That event was seen as opening the epoch of studying GRBs at even higher redshifts, with possible relevance to Population III stars. While GRB 050904 was a standard "long-soft" GRB, and therefore most likely originating from a core-collapse "hypernova" (e.g. Stanek et al. 2003), Population III stars, lacking metals, might be hard pressed to lose their envelopes (e.g. Kudritzki 2002), so binaries might be needed to do the trick (e.g. Bromm & Loeb 2005).

4. In a more local Universe, Stepien (2005) discussed a possible solution to the "Kuiper paradox" seen in the binary W UMa-type systems. A large population of equal-mass binaries would be certainly relevant, although possibly not crucial, to his proposed scenario.

5. Krumholz, McKee and Klein (2005) argue that "Stars Form By Gravitational Collapse, Not Competitive Accretion" (but see e.g. Bate 2000). It would be most interesting to see if the existence of large population of twins favors any of the existing star formation models and in fact Bonnell & Bate (2005) claim exactly that.

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